Original Research Paper

Anthropogenic pressures within the breeding range of the Hen Harrier (*Circus cyaneus*) in Ireland

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Summary

Capsule

Patterns in the frequency and co-occurrence of anthropogenic pressures associated with suitable breeding habitat for Hen Harriers demonstrates the need for specific, focussed management and policy options aimed at mitigating impacts on this threatened population.

Aims

To describe anthropogenic pressures and threats in the upland breeding range of Hen Harriers and to explore their potential impacts on the declining Hen Harrier population.

Methods

We used text mining, mixed effects models, Principal Component Analysis and clustering methods to explore anthropogenic pressures on suitable breeding and foraging habitats for Hen Harriers in Ireland, based on the 2015 national breeding Hen Harrier survey data.

Results

Mixed-effects models described a strong influence of agriculture, forestry, predator activity and recreational activities on survey areas that contained Hen Harrier territories. Cluster analyses described three discrete pressure clusters and showed consistent co-occurrence of independent pressures.

Conclusions

Areas of suitable habitat for Hen Harriers in the uplands overlap with areas that experience anthropogenic pressures known to negatively impact on this vulnerable bird species. Combined with clear evidence for the co-occurrence of multiple pressures at regional scale, this demonstrates a clear need for statutory agencies to consider the potential cumulative impacts of individual pressures when developing conservation strategies for Hen Harriers.

48

49 **Introduction**

50 Many species, worldwide, are threatened by anthropogenic pressures that require intervention
51 to mitigate or eliminate their negative impacts (Wilcove et al. 1998; Carroll et al. 2015; Di
52 Minin et al. 2016). Such pressures can result in stress responses or reduced fitness in wildlife
53 that, in some cases, has severe impacts on individuals or populations (Wilcove et al. 1998;
54 Taylor & Knight 2003; Johnson et al. 2005; Ciuti et al. 2012; Coetzee & Chown 2016).
55 Conservation processes typically aim to prevent species population declines and extinctions
56 (Soule 1985). However, conservation policy must also be cognisant of the sustainable
57 management of environmental resources and other activities of economic and social
58 importance including commercial forestry, agriculture and recreation (Young et al. 2005;
59 Kareiva & Marvier 2012; Kennedy et al. 2016; Vangansbeke et al. 2017)

60 Human activities in the vicinity of breeding birds can lead to increased rates of nest
61 desertion (White & Thurow 1985), and reduced rates of site occupancy (Webber et al. 2013),
62 territory establishment (Bötsch et al. 2017), breeding success (Balotari-Chiebao et al. 2016)
63 and survival (Ruhlen et al. 2003; including illegal killing, e.g. Smart et al. 2010).
64 Quantifying the extent and ecological relevance of each of these impacts informs our
65 understanding of human-wildlife interactions and underpins conservation and resource
66 management processes. It is essential, therefore, that human activities that have the potential
67 to affect wildlife, particularly vulnerable species of conservation concern, are properly
68 assessed and understood, so that appropriate measures can be developed to facilitate
69 conservation and sustainable land and resource use.

70 Hen Harriers (*Circus cyaneus*) are medium-sized raptors that nest largely upland
71 areas, typically heather moorland in Britain (Redpath et al. 1998; Amar et al. 2008; Watson
72 2017), during the summer breeding season. Upland habitats in Ireland have been subjected to

degradation and land-use change and, in the absence of their preferred open heath and blanket bog nesting habitat. As a result of a large-scale afforestation programme in the Republic of Ireland from the 1950s and the conversion of 'traditional' open habitats to forest, Hen Harriers in Ireland are frequently associated with young (i.e. pre-thicket) conifer plantations that provide them with areas for nesting and foraging (Wilson et al. 2009; Irwin et al. 2012; Wilson et al. 2012; Ruddock et al. 2016). Anthropogenic impacts such as afforestation and forest management (NPWS 2015), landscape degradation and land-use change (Wilson et al. 2009; Wilson et al. 2012), livestock grazing (O'Rourke & Kramm 2009), illegal burning (Renou-Wilson et al. 2011), peat extraction (O'Riordan et al. 2015), recreation (Hynes & Buckley 2007) and wind energy development (Wilson et al. 2017) could have important implications for breeding Hen Harriers. It should be noted that the level of persecution observed in Britain (e.g. Redpath et al. 2010; Murgatroyd et al. 2019) is not observed in Ireland as there are no areas that are managed solely for driven grouse shooting. However, raptors are known to migrate within the British Isles (Mead, 1973) and persecution of Hen Harriers in Britain could have hitherto undescribed impacts on the Irish population. The Hen Harrier population in Ireland is of national conservation concern (Colhoun & Cummins 2013), with a population of between 108 and 157 breeding pairs recorded in the most recent national survey (Ruddock et al. 2016). The species is listed under Annex I of the European Commission Birds Directive (2009/147/EC) that requires Member States to designate Special Protection Areas (SPAs) for their survival and reproduction. Six Hen Harrier SPAs containing important breeding areas for the species were designated in Ireland in 2007.

Hen Harrier conservation research in Ireland to date has focussed on the impacts of afforestation (Irwin et al., 2012; Wilson et al., 2009, 2012) and wind farm development (Fernández-Bellon et al., 2015; Wilson et al., 2017) on their populations, as required to inform conservation management. Due to the targeted nature of previous research, very little

information is available in the published literature regarding the broader range of anthropogenic pressures that might impact breeding Hen Harriers and associated foraging and breeding habitat. Furthermore, previous research has considered how individual pressures impact separately and in specific contexts while consideration of the synergies between pressures is lacking. To address these gaps, we explored data on anthropogenic pressures affecting Hen Harriers within their breeding range in Ireland, with the aim of deriving information that would inform conservation and management processes for this threatened species.

Materials and methods

The 2015 National Survey of Breeding Hen Harrier in Ireland was conducted between April and August 2015 in suitable Hen Harrier habitat in upland areas, largely, but not exclusively, between 200m and 600m above sea level (asl) and within the Hen Harrier breeding range (Ruddock et al. 2016). Survey squares of 10 km^2 (n = 268) were defined using the Irish National Grid (Fig. 1a). Anthropogenic activities that could potentially impact on breeding Hen Harriers ('pressures' from hereon) were recorded from vantage points within each survey square during each of 4-6 dedicated watches per square, during the breeding season. Where sites were occupied, vantage points were a minimum of 500 m from nests sites. Vantage points were identified *a-priori* based on habitat suitability, topographical constraints and the potential for observers to cause disturbance to breeding birds (Ruddock and Whitfield 2007; Philip Whitfield et al. 2008). Hen Harrier territories (n = 100, across 54 survey squares) were recorded where identified; occupancy was based on observations of Hen Harrier breeding behaviour and the repeated presence of birds (Ruddock et al., 2016). Data were collected by staff, members and volunteers from the National Parks & Wildlife Service

(NPWS), BirdWatch Ireland (BWI), Irish Raptor Study Group (IRSG), Golden Eagle Trust (GET), university researchers, and independent commercial and voluntary ornithological surveyors

Pressures were divided into 47 discrete categories (Appendix I) aligned with the EU Birds Directive (2009/147/EC) reporting matrix. The frequency of occurrence of each pressure within 2 km of vantage point locations was recorded within each survey square. Initial exploration of the data revealed extreme outliers, therefore we adopted a precautionary approach and applied consistent thresholds throughout. Values for individual pressures that occurred beyond two standard deviations (SDs) from the mean were replaced with the maximum value as defined by the aforementioned threshold, rounded to the nearest whole integer. This allowed us to capture the prevalence of each pressure at each location while mitigating over-inflation. The sum frequency of each pressure was calculated (i) across all survey squares where the total number of recorded pressures was >0 (n=146; Appendix II); (ii) across squares located within SPA boundaries only (n=24); and (iii) across squares where confirmed Hen Harrier territories were present (n=54). It was necessary to account for variation in survey effort as the number of visits made to vantage points varied between observers. Therefore, a Pressure Index (PI) was created, where the total number of pressures was divided by the total number of visits (Ruddock et al. 2016). PI scores were normalised between 0 and 1 to facilitate comparisons between sites. General Linear Models (GLMs) were used to investigate differences between PI scores – with zero counts removed and remaining data log transformed to meet model assumptions – where PI was the dependent variable and the location of vantage points relative to SPA boundaries (inside/outside) and confirmed Hen Harrier territories (present/absent) were explanatory variables. Models explored each category (SPA boundaries and Hen Harrier territories) independently as well as part of a fully-factorial model that included an interaction term.

147 Principal Component Analysis (PCA; Jolliffe & Cadima, 2016) and linear mixed-
148 effects models were used to investigate relationships between the presence/absence of Hen
149 Harrier territories and pressure categories. Data were Box Cox transformed to remove
150 skewness, centred and standardised to have a $\bar{x}$ =0 and σ = 1 prior to analysis. Principal
151 Components (PCs) that cumulatively accounted for >50% of the variance were retained for
152 inclusion in models. The presence/absence of Hen Harrier territories (Fig. 1b) was entered as
153 a binary dependent variable, retained PCs were included as explanatory variables and
154 surveyor identity was included as a random variable. Model permutations were ranked using
155 the Akaike Information Criterion (AIC); the top subset of models was found within ΔAIC $\leq$2
156 units (Burnham & Anderson 2002).

157 Cluster analysis was used to quantify associations between individual pressure
158 categories across all survey squares. The various methods that comprise cluster analyses
159 provide a means of classifying multivariate data into subgroups according to the similarity of
160 their attributes, thus revealing the underlying structure (Everitt et al. 2009). We calculated the
161 distance of each recorded pressure from the cluster's mean using a Euclidean distance index
162 and applied the Ward error sum of squares hierarchical clustering method (Ward 1963) to the
163 resultant data. The optimal number of clusters (k_t) was identified using average silhouettes
164 (Kaufman & Rousseeuw 1990) and Approximately Unbiased (AU) *p*-values with multiscale
165 bootstrap resampling (B = 10,000) where clusters with $p \geq 0.95$ were strongly supported
166 (Suzuki and Shimodaira 2006). All data analyses and plotting were carried out using the
167 statistical programme R (R Core Team 2017), specifically the packages *cluster* (Maechler et
168 al. 2018) and *pvclust* (Suzuki and Shimodaira 2015), *dendextend* (Galili 2015), *nlme*
169 (Pinheiro et al. 2017) and *caret* (Kuhn 2017). Data are subject to data-sharing agreements
170 and, therefore, cannot be redistributed. However, R code used for data exploration and
171 analyses are available at http://doi.org/10.5281/zenodo.3549584.

Results

A total of 2,873 individual pressure occurrences were recorded during this study. There were no anthropogenic pressures recorded in 45% of survey squares. The most frequently recorded pressures across all survey squares were *forest management and use* (13% of occurrences), *paths, tracks, forest roads* (11%), *uncontrolled burning* (6%) and *wind energy production* (6%). Similar pressures were recorded inside and outside of SPA boundaries: *forest management and use* (14% and 11% of occurrences, respectively), *paths, tracks, forest roads* (10%, 0%), forest planting on open ground (0%, 8%), *uncontrolled burning* (6.6%, 7%) and *wind energy production* (9.5%, 7%). The most frequently recorded pressures associated with confirmed Hen Harrier territories were *loss of habitat features* (13.7%), *dispersed habitation* (10.5%), *paths, tracks, forest roads* (9.2%) and *forest management* (8.1%). In contrast, pressures at vantage points not associated with Hen Harrier territories were *forest management and use* (16%), off-road motorised driving (12%), *forest planting on open ground* (11%), and *mechanical removal of peat* (11%).

Pressure Indices varied between survey squares (Fig. 1c) and only one survey square had a PI > 0.5. Survey squares where vantage points occurred within SPAs had a maximum PI of 0.22 ($\bar{x}$ = 0.08 ± 0.07), which was significantly higher than those outside SPAs (t = 0.028; β = -0.44 ± 0.20; P = 0.03). Survey squares where vantage points were associated with Hen Harrier territories had a maximum PI of 0.42 ($\bar{x}$ = 0.10 ± 0.09; Appendix I), which was significantly higher than those that were not associated with territories (t = 0.038; β = -0.39 ± 0.19; P = 0.04; Table 1).

Both silhouette and AU clustering methods supported three discrete clusters ($P \geq$ 0.05). The largest cluster (*ii*) consisted of 25 pressure categories while the smallest (*iii*) was

196 the most distinct and consisted of five pressure categories. One sub-cluster was statistically
197 supported (*iv)* and was comprised of 17 pressure categories (Fig. 2).

198 A total of seven Principal Component axes, accounting for >50% of the total variance,
199 were retained for inclusion in mixed-effects models investigating the relationship between the
200 presence/absence of Hen Harrier territories and associated pressures. The top subset of
201 models (ΔAIC $\leq$2) included PC1, PC2 and PC3. PC1 accounted for the greatest proportion of
202 total variance (20%); loadings were most strongly weighted towards aspects of agricultural
203 and forestry activity and predators; PC2 (8%) was weighted towards forest management and
204 site access; and PC3 was weighted towards forest clearance and recreational activities (Table
205 2). The best approximating model was positively influenced by PC1 and PC3, and negatively
206 influenced by PC2 (Table 2). It should be noted that PC1 includes *nest destruction*, *predation*
207 *by birds* and *predation by mammals*. These pressures can only occur where Hen Harriers nest,
208 hence the observed positive association is to be expected.

209

210 **Discussion**

211 Our results show that suitable Hen Harrier breeding habitats in Ireland are subjected
212 to a wide range of anthropogenic pressures that could have significant implications for this
213 vulnerable species. The number and variety of pressures recorded demonstrates the potential
214 of disturbance to prospecting Hen Harriers early in the breeding season and/or to foraging
215 Hen Harriers once territories have been established (e.g. González et al. 2006). Furthermore,
216 the co-occurrence of pressures as described by cluster analyses demonstrates the considerable
217 potential for cumulative effects. Anthropogenic impacts are not homogenous in their severity
218 or extent. This is certainly true in the current study, where some pressures will have more
219 severe consequences for Hen Harriers or will act at different spatial scales. However, there is

220 a dearth of quantitative data on the impacts of described pressures on Hen Harriers. Our
221 results highlight the importance of managing pressures in an integrated manner rather than on
222 an individual basis. This provides support for the effective management of suitable breeding
223 areas to minimise the potential impact of anthropogenic pressures on vulnerable Hen Harrier
224 populations.

225 Planted forests and the presence of tracks or roads were recorded at high frequencies
226 in all survey squares across Ireland. Large areas of Irish upland habitat have been afforested
227 in recent decades and total forest cover is expected to continue to increase from the current
228 11% to as much as 18% in the next 30 years (NPWS 2015). In the absence of their traditional
229 open heath and blanket bog habitat, Hen Harriers in Ireland are frequently associated with
230 young (i.e. pre-thicket) conifer plantations that provide areas that Hen Harriers use for
231 nesting and foraging (Wilson et al. 2009; Irwin et al. 2012; Wilson et al. 2012; Ruddock et al.
232 2016). Hen Harriers cannot use use closed-canopy forests for breeding or foraging, therefore
233 the maturation of the existing forest estate threatens to deprive Hen Harriers of already scarce
234 breeding habitat, while further increases in forest cover could also lead to increased habitat
235 fragmentation and subsequently reduce the capacity of the landscape to support breeding
236 pairs. Recreational activities were also strongly associated with survey squares containing
237 Hen Harrier territories. Systematic reviews have demonstrated that recreational activities can
238 negatively impact breeding birds (e.g. Steven et al. 2011; Larson et al. 2016) including
239 above-ground foragers (Bötsch et al. 2017) and upland species such as Golden Plovers
240 (*Pluvialis apricarius*; Finney et al. 2005). Thus, there exists the potential for disturbance of
241 prospecting Hen Harriers early in the breeding season and/or foraging Hen Harriers once
242 territories have been established.

243 Mammalian and avian predators were among the factors strongly associated with Hen
244 Harrier territories. O'Donoghue (2010) attributed 55% of all nest failures in south and west

Ireland in 2007 and 2008 to predation events and foxes (*Vulpes vulpes*) have been observed depredating Hen Harrier chicks via remote-sensing camera traps (Irwin et al. 2012; Fernández-Bellon et al. 2017). Other potential predators of Hen Harrier nests in Ireland include Pine Marten (*Martes martes*), American Mink (*Neovison vison*), Stoat (*Mustela erminea*), Raven (*Corvus corax*) and Hooded Crow (*Corvus corone corvix*) (Picozzi, 1984; Fernández-Bellon et al., 2018a). These predators can have substantial negative impacts on ground-nesting birds (Paton 1994) as eggs and young chicks are particularly vulnerable to predation when parents are absent. Populations of generalist predators may be bolstered by changes in land-use and management, including afforestation and other forms of habitat fragmentation (e.g. Prestt, 1965; Haydon & Harrington, 2000; Chalfoun et al. 2002; Twining et al. 2019). However, data on the abundance and activity of upland predators in Ireland are scarce; efforts to investigate such may be of considerable benefit to the conservation of Hen Harriers.

It is notable that wind energy production was recorded more frequently within SPA boundaries than outside but was rarely recorded in survey squares that contained breeding Hen Harriers (3.3%) in this study, perhaps indicating avoidance of wind farms for breeding purposes (also see Wilson et al. 2017). Indeed, windfarm construction activity has been implicated in the desertion of traditional breeding sites in Ireland (O'Donoghue et al. 2011). The construction and operation of wind turbines can have both lethal and sub-lethal impacts on birds (Drewitt & Langston 2006; Marques et al. 2014; Wilson et al. 2015; Balotari-Chiebao et al. 2016; Smith & Dwyer 2016; Fernández-Bellon et al. 2018; Thaker et al. 2018). The Republic of Ireland is committed to EU targets on renewable energy including a national target of 40% electricity from renewables by 2020, which is likely to involve the construction of additional wind farms (DCCAE 2010). Wind energy developments tend to be upland-focussed and future, large-scale expansion may pose a threat to breeding Hen Harriers. A bird

sensitivity mapping tool has been developed to guide the siting of future wind energy developments in Ireland in relation to the distribution of species of conservation concern, including Hen Harrier (McGuinness et al. 2015). However, there is as yet no mandatory obligation on developers to use this tool.

The timing of disturbance events may be a key consideration and many sources of disturbance may already be present at the onset of breeding, when pairs are establishing territories. Furthermore, other pressures such as peat extraction or illegal burning may not occur until after laying and, hence, can impact on parental care and, ultimately, breeding success. Current mitigation measures for Hen Harriers in Ireland adopt a reactive approach where circular 'High Likelihood Nesting Areas' (HNLA, formerly Red Areas) of high sensitivity to Hen Harriers, that contain nesting pairs and with a radius of 1.2 km, are added to the HNLA network when new breeding pairs are identified (NPWS 2015). Forestry operations that may cause disturbance are regulated within these HNLAs during the breeding season (Forest Service 2012). However, the protection afforded by HNLAs only applies to known pairs within the SPA network. Therefore, all other pairs that are outside of the SPA network (>50% of the breeding population; Ruddock et al. 2016), remain vulnerable to direct disturbance from forest management activities during the nesting season. Moreover, breeding Hen Harriers have been recorded travelling as far as 11 km from active nests (Irwin et al. 2012; Arroyo et al. 2014) and human activities and impacts in the wider landscape can have impacts on the physiology (Abbasi et al. 2017) and mortality (Ferrer & Hiraldo 1993) of birds. Human activities within the foraging range of breeding Hen Harriers could result in patch avoidance and/or stress-related responses in foraging birds, potentially keeping them away from the nest for longer periods of time and subsequently increasing chick vulnerability. It is possible that Hen Harriers in Ireland have the capacity to develop a tolerance for human activities during the breeding season. However, given their small

population size and conservation status, the precautionary principle suggests that human activities should be strictly regulated in areas of suitable Hen Harrier breeding and foraging habitat, particularly during key breeding months. Furthermore, pressures and their potential impacts on breeding Hen Harriers must be placed in a broader context that includes the timing of pressure occurrence, the composition of the wider landscape and the conservation of suitable habitat.

The pressures described herein represent potential disturbances to Hen Harriers throughout their breeding cycle and therefore may have important consequences for long-term population persistence or recovery. Recent research suggests that the same pressures impact another upland bird of prey, the Short-eared Owl (*Asio flammeus*), across their European range (Fernández-Bellon, unpubl. data). Thus, we recommend the following actions to enhance conservation benefits for Hen Harriers and other sensitive upland species and habitats: i) restrict forestry activities within the known hen Harrier range during the Hen Harrier breeding season (April – August) by using targeted surveys to detect Hen Harrier presence, thereby ensuring that forest management activities can be undertaken in areas that do not hold Hen Harriers during the summer months; ii) quantify the abundance and activity of upland predators and explore options for predator control, where appropriate; iii) discourage recreation and non-licensed forestry-related activities in areas known to hold Hen Harriers, throughout the breeding season, supported by a programme of community engagement, awareness-raising and upland signage; and iv) improve lines of communication between the relevant stakeholders so that potentially damaging activities can be identified at the earliest stages.

Failure to mitigate anthropogenic disturbances in upland areas of potentially suitable Hen Harrier breeding habitat, whether inside or outside of SPAs, could have negative consequences for this already vulnerable population. To date, none of the SPAs in the Hen

Harrier Natura 2000 network possess management plans, one of the key requirements of such sites, over a decade on from designation in 2007, and a Hen Harrier Threat Response Plan, initiated by the National Parks & Wildlife Service in the Republic of Ireland in 2016 with wide stakeholder consultation, has yet to be published. Furthermore, connecting multiple pressures is a key issue for conservation management, and Hen Harrier conservation policies must comprehensively account for cumulative anthropogenic impacts at regional level. Successful mitigation and management would represent a significant step towards the conservation of Hen Harriers in Ireland and serve as an example for upland conservation initiatives in Europe.

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Appendix I

Pressure codes and descriptions. Reproduced from Ruddock et al. (2016). Adapted from the EU Birds Directive reporting matrix (http://cdr.eionet.europa.eu/help/birds_art12).

Code	Description of pressure
A1	Modification of cultivation practices
A2	Agricultural intensification
A3	Mowing / cutting of grassland
A4	Abandonment / lack of mowing
A5	Intensive grazing
A6	Non-intensive grazing
A7	Abandonment of pastoral systems, lack of grazing
A8	Fertilisation (agricultural)
A9	Removal of hedges and copses or scrub
B1	Forest planting on open ground (increase in forest area, planting e.g. on grassland, heathland)
B2	Forest and plantation management & use
B3	Forest replanting (i.e. replanting on forest ground after clear-cutting)
B4	Forest clearance (clear-cutting, removal of all trees)
B5	Thinning of tree layer
B6	Fertilisation (forestry)
B7	Other forest activities (e.g. erosion due to forest clearing, fragmentation)
C1	Hand cutting of peat
C2	Mechanical removal of peat
C3	Wind energy production
D1	Paths, tracks, cycling tracks (includes non-paved forest roads)
D2	Roads, motorways (all paved/ tarred roads)
D3	Utility and service lines (e.g. power-lines, pipelines)
D4	Aircrafts or flightpaths
D5	Improved access to site
E1	Urbanisation, residential and commercial development
E2	Dispersed habitation (i.e. little or no human disturbance)
F1	Nest destruction
F2	Illegal killing (e.g. shooting, trapping, poisoning)
G1	Human intrusions and disturbances
G2	Outdoor sports and leisure activities, recreational activities
G3	Walking, horse-riding and non-motorised vehicles
G4	Motorised vehicles
G5	Off-road motorised driving
G6	Other outdoor sports and leisure activities
G7	Military manoeuvres
H1	Pollution (e.g. water pollution, fly-tipping)
J1	Natural fires
J2	Controlled burning (e.g. strip burning for grouse management)

J3	Uncontrolled burning (e.g. widespread unmanaged or malicious burning)
J4	Modification of water levels or waterbodies
J5	Reduction or loss of specific habitat features (e.g. removal of hedgerows, deep heather, scrub, walls, drains)
J6	Reduction of prey availability
J7	Anthropogenic reduction of habitat connectivity (i.e. fragmentation such as by removal of large areas of habitat or creation of barriers between habitats)
K1	Interspecific faunal relations - predation (by other birds e.g. crows)
K2	Interspecific faunal relations - predation (by mammals e.g. foxes)
X	No pressures recorded
O	Other pressures not listed above; noted pressures included bracken encroachment, cattle, drainage, helicopter training, quarrying and shooting.

Appendix II

Summary data for all survey squares where the total number of pressures was >0. SPA = location of survey site relative to Special Protection Area (SPA) boundaries: 1 = inside; 0 = outside. PI = standardised Pressure Index (see main text).

Site number	Total number of pressures	Total number of observer visits	Total number of Hen Harrier territories	SPA	PI
1	1	5	0	0	0.01
2	10	45	0	0	0.02
3	22	16	0	0	0.10
4	8	10	0	0	0.06
5	10	9	0	0	0.08
6	23	8	0	0	0.21
7	5	3	0	0	0.12
8	4	8	0	0	0.04
9	12	6	0	0	0.15
10	34	17	1	0	0.15
11	14	14	3	0	0.07
12	16	14	1	0	0.08
13	19	22	1	0	0.06
14	9	2	0	0	0.33
15	2	3	0	0	0.05
16	4	3	0	0	0.10
17	9	12	1	0	0.06
18	17	35	2	1	0.04
19	9	11	2	0	0.06
20	2	3	0	0	0.05
21	6	30	2	0	0.01
22	7	12	0	0	0.04
23	8	10	1	0	0.06
24	3	5	1	0	0.04
25	6	43	1	0	0.01
26	15	13	1	1	0.09
27	23	78	1	1	0.02
28	10	8	0	0	0.09
29	4	8	0	0	0.04
30	3	13	0	0	0.02
31	3	6	0	0	0.04
32	18	31	0	0	0.04
33	9	9	0	0	0.07
34	20	78	3	1	0.02
35	9	29	0	0	0.02
36	2	6	0	0	0.02
37	2	2	0	0	0.07

38	6	3	0	0	0.15
39	6	5	0	0	0.09
40	5	82	2	1	0.00
41	7	10	1	1	0.05
42	1	44	1	0	0.00
43	13	142	7	1	0.01
44	5	3	0	0	0.12
45	16	21	0	0	0.06
46	3	3	0	0	0.07
47	3	2	0	0	0.11
48	24	8	0	0	0.22
49	3	1	0	0	0.22
50	5	2	0	0	0.19
51	6	11	0	0	0.04
52	19	10	0	0	0.14
53	9	9	0	0	0.07
54	6	2	0	0	0.22
55	26	5	0	0	0.39
56	1	8	0	0	0.01
57	65	23	1	1	0.21
58	95	32	2	1	0.22
59	6	1	0	0	0.44
60	17	3	0	0	0.42
61	122	60	2	1	0.15
62	59	11	0	0	0.40
63	17	11	1	0	0.11
64	6	2	0	0	0.22
65	33	17	1	0	0.14
66	56	40	2	1	0.10
67	68	62	2	1	0.08
68	2	5	0	0	0.03
69	13	79	5	1	0.01
70	17	60	4	1	0.02
71	17	4	0	0	0.31
72	81	50	2	0	0.12
73	1	5	0	0	0.01
74	54	25	0	0	0.16
75	40	21	2	1	0.14
76	8	34	2	1	0.02
77	2	31	0	0	0.00
78	2	43	2	1	0.00
79	33	17	0	0	0.14
80	9	8	0	0	0.08
81	4	1	0	0	0.30

82	2	2	0	0	0.07
83	40	50	2	0	0.06
84	5	12	1	0	0.03
85	54	12	0	0	0.33
86	5	7	0	0	0.05
87	48	36	2	1	0.10
88	2	1	0	0	0.15
89	113	143	5	0	0.06
90	3	1	0	0	0.22
91	74	21	3	0	0.26
92	14	9	0	0	0.12
93	150	60	2	1	0.19
94	19	11	1	0	0.13
95	53	25	2	0	0.16
96	35	15	2	1	0.17
97	73	14	1	0	0.39
98	11	11	0	0	0.07
99	21	26	1	1	0.06
100	5	11	1	0	0.03
101	11	17	1	0	0.05
102	20	5	0	0	0.30
103	15	4	1	0	0.28
104	15	25	0	0	0.04
105	23	10	0	0	0.17
106	6	5	0	0	0.09
107	4	3	0	0	0.10
108	13	11	0	0	0.09
109	5	20	2	0	0.02
110	8	17	1	1	0.03
111	31	15	1	0	0.15
112	85	15	3	0	0.42
113	7	3	0	0	0.17
114	2	9	0	0	0.02
115	26	9	0	0	0.21
116	5	54	2	1	0.01
117	14	4	0	0	0.26
118	2	3	0	0	0.05
119	16	24	0	0	0.05
120	15	9	0	0	0.12
121	6	8	0	0	0.06
122	9	11	0	0	0.06
123	6	8	0	0	0.06
124	4	6	0	0	0.05
125	11	4	0	0	0.20

126	14	7	0	0	0.15
127	8	9	0	0	0.07
128	8	4	0	0	0.15
129	27	19	0	0	0.11
130	10	16	0	0	0.05
131	10	16	0	0	0.05
132	4	2	0	0	0.15
133	13	10	0	0	0.10
134	54	4	0	0	1.00
135	2	1	0	0	0.15
136	14	12	1	1	0.09
137	9	13	0	0	0.05
138	18	10	0	0	0.13
139	6	3	0	0	0.15
140	86	79	1	0	0.08
141	9	8	1	0	0.08
142	23	21	3	0	0.08
143	1	3	0	0	0.02
144	100	23	1	0	0.32
145	1	3	0	0	0.02
146	1	16	0	0	0.00

Appendix III

Linear mixed-effects model results for pressures – expressed as Principal Components (PC) - associated with confirmed Hen Harrier territories (present/absent). Factors retained in the top subset of *n* models (< Δ2 AIC) are highlighted. Constituent pressures along with pressure codes and associated loadings (coefficients; in parentheses) are given. Pressure codes are taken and descriptions are abbreviated from those given in Ruddock et al. (**2016**; see Appendix I). Regression coefficients ($\beta \pm$ SE) and significance of contributory PCs are given, where * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$. For constituent pressures in PC1-3, see Table 2 in the main text.

Principal Component (% variance explained)	**Pressure**	***β***	**± SE**	***t***	
PC1		0.025	0.007	3.52	**
PC2		-0.046	0.009	-5.05	***
PC3		0.044	0.011	-3.91	**
PC4	Non-intensive grazing (A6; 0.51)	0.010	0.013	0.78	
(5%)	Agricultural fertilisation (A8; 0.32)				
	Urbanisation, residential and commercial development(E1; 0.50)				
PC5	Hand cutting of peat (C1; -0.40)	-0.004	0.014	-0.27	
(5%)	Aircrafts or flightpaths (D4; -0.30)				
	Reduction of prey availability (J6; -0.52)				
	Other pressures not listed (O; -0.38)				
PC6	Agricultural intensification (A2; 0.27)	-0.005	0.014	-0.38	
(4%)	Hand cutting of peat (C1; -0.25)				
	Roads, motorways (D2; 0.34)				
	Dispersed habitation, i.e. little or no human disturbance (E2; 0.37)				
	Off-road motorised driving (G5; -0.38)				
	Other outdoor sports and leisure activities (G6; 0.29)				
PC7	Hand cutting of peat (C1; 0.29)	0.006	0.015	0.41	
(4%)	Dispersed habitation, i.e. little or no human disturbance (E2; 0.28)				
	Pollution (H1; 0.26)				
	Modification of water levels or waterbodies (J4; 0.27)				

Reduction of prey availability (J6; -0.27)
Other pressures not listed (O; -0.32)

Table 1. General Linear Model (GLM) results for regional differences in pressures on Hen Harrier breeding habitat - expressed as a Pressure Index (PI; log transformed). *s* = Special Protection Areas (SPA; inside/outside); *r* = confirmed territories (present/absent). Regression coefficients ($\beta \pm$ SE) and significance of contributory variables are given, where * = $p < 0.05$.

Model	**Variable**	***t***	***β*** **(± SE)**
PI ~ *r*	*r*	0.038	-0.39 ± 0.19*
PI ~ *s*	*s*	0.028	-0.44 ± 0.20*
PI ~ *r* + *s* + *r***s*	*s*	-0.515	-0.14 ± 0.28
	r	-0.683	-0.16 ± 0.23
	*s***r*	-1.128	-0.46 ± 0.40

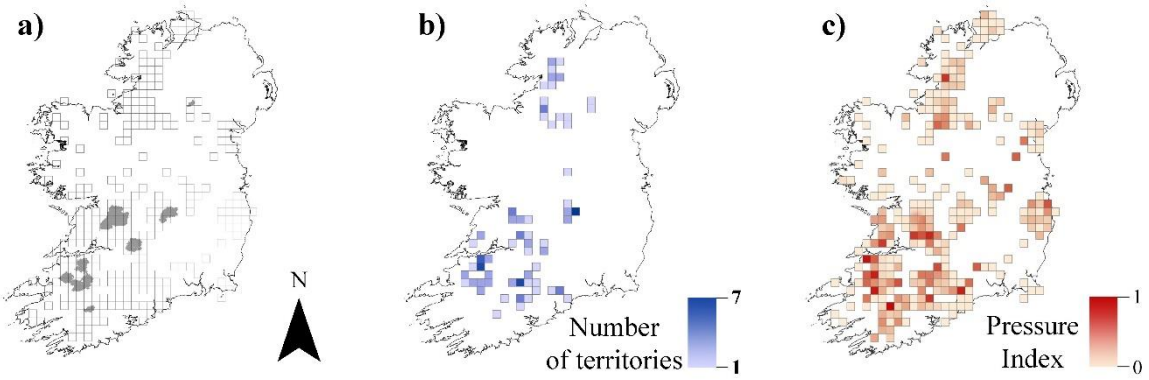
Table 2. Linear mixed-effects model results for pressures – expressed as Principal Components (PC) - associated with confirmed Hen Harrier territories (present/absent). Models were evaluated according to their Akaike's Information Criterion (AIC) value. Factors retained in the top subset of *n* models (< Δ2 AIC) are highlighted. Constituent pressures along with pressure codes and associated loadings (coefficients; in parentheses) are given. Pressure codes are taken and descriptions are abbreviated from those given in Ruddock et al. (**2016;** see **Appendix I**). Regression coefficients ($\beta \pm$ SE) and significance of contributory PCs are given, where * = p < 0.05, ** = p < 0.01, and *** = p < 0.001. For constituent pressures in PC4-7, see Appendix III.

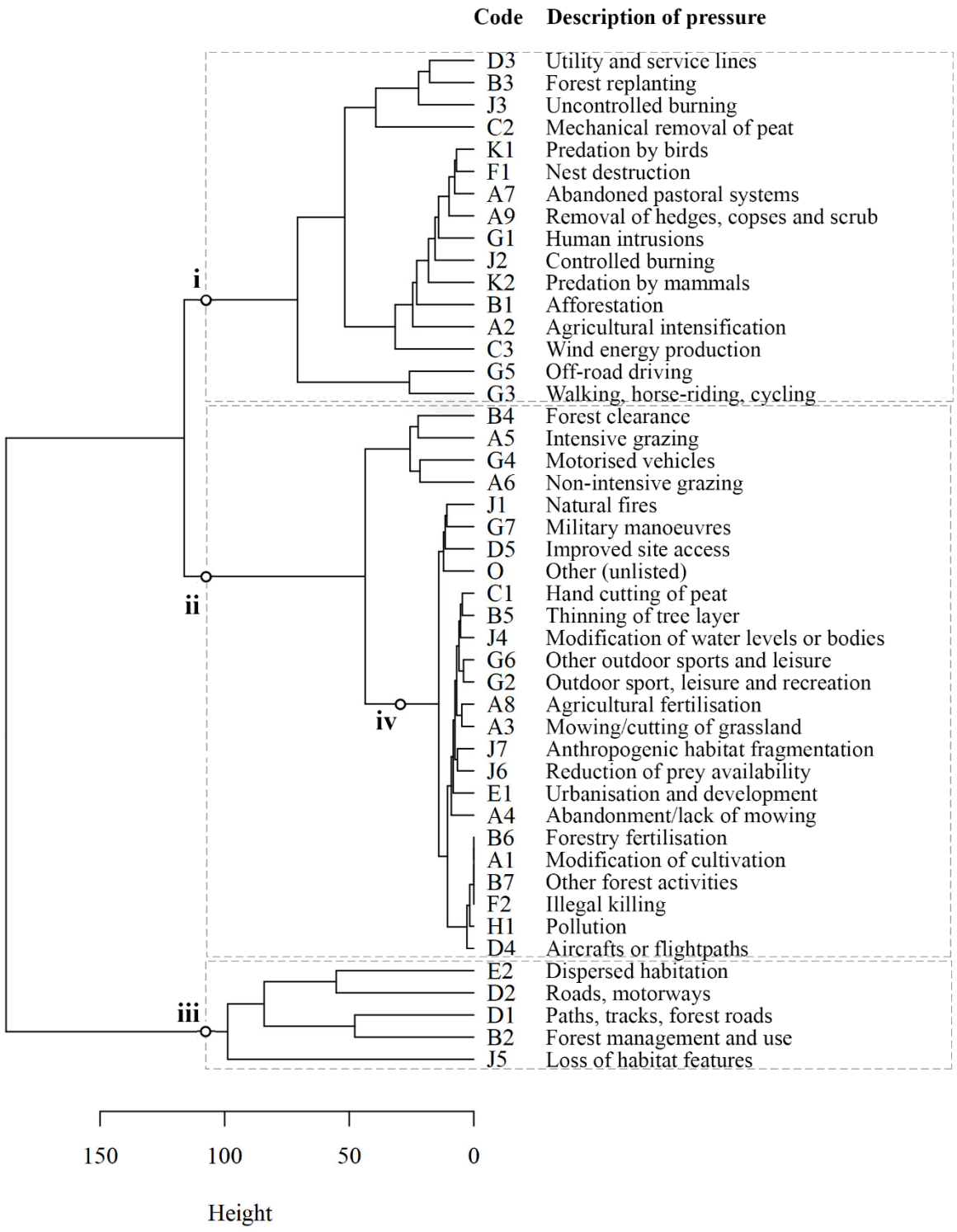
Principal Component (% variance explained)	**Pressure**	***β***	**± SE**	***t***	
PC1	Abandoned pastoral systems (A7; 0.29)	0.025	0.007	3.52	**
(21%)	Removal of hedges, copse and scrub (A9; 0.29)				
	Forest replanting (B3; 0.27)				
	Nest destruction (F1; 0.29)				
	Controlled burning (J2; 0.27)				
	Predation by birds (K1; 0.31)				
	Predation by mammals (K2; 0.26)				
PC2	Forest management and use (B2; -0.28)	-0.046	0.009	-5.05	***
(10%)	Forest clearance (B4; -0.30)				
	Thinning of tree layer (B5; -0.26)				
	Paths, tracks, forest roads (D1; -0.35)				
	Roads, motorways (D2; -0.33)				
	Natural Fires (J1; -0.30)				
PC3	Dispersed habitation (E2; -0.32)	0.044	0.011	-3.91	**
(7%)	Outdoor sport, leisure and recreation (G2; -0.35)				
	Walking, horse-riding, cycling (G3; -0.42)				
	Motorised vehicles (G4; -0.29)				
	Off-road driving (G5; -0.32)				
	Other outdoor sports and leisure (G6; -0.30)				

PC4	0.010	0.013	0.78
PC5	-0.004	0.014	-0.27
PC6	-0.005	0.014	-0.38
PC7	0.006	0.015	0.41

Figure 1. Maps of Ireland showing **(a)** survey squares and Special Protection Areas (SPAs, as indicated by grey polygons), **(b)** the total number of confirmed Hen Harrier territories per square, and **(c)** pressure indices derived from cumulative observations of pressures within each survey square. See Appendix II for square-specific data.

Figure 2. Relationships between pressures associated with potentially suitable breeding habitat for Hen Harriers. Pressure codes are taken and descriptions abbreviated from those given in Ruddock et al. (2016). Dashed grey rectangles indicate outermost clusters identified via the silhouette method and multiscale bootstrapping (10,000 iterations; Approximately Unbiased [AU] $p \leq 0.05$). ○ = clusters supported at AU $p \leq 0.05$. For detailed pressure definitions, see **Appendix I**.


a)
N
b)
Number
of territories
7
1
c)
Pressure
Index
1
0


Code
Description of pressure
D3 Utility and service lines
B3 Forest replanting
J3 Uncontrolled burning
C2 Mechanical removal of peat
K1 Predation by birds
F1 Nest destruction
A7 Abandoned pastoral systems
A9 Removal of hedges, copses and scrub
G1 Human intrusions
J2 Controlled burning
K2 Predation by mammals
B1 Afforestation
A2 Agricultural intensification
C3 Wind energy production
G5 Off-road driving
G3 Walking, horse-riding, cycling
B4 Forest clearance
A5 Intensive grazing
G4 Motorised vehicles
A6 Non-intensive grazing
J1 Natural fires
G7 Military manoeuvres
D5 Improved site access
O Other (unlisted)
C1 Hand cutting of peat
B5 Thinning of tree layer
J4 Modification of water levels or bodies
G6 Other outdoor sports and leisure
G2 Outdoor sport, leisure and recreation
A8 Agricultural fertilisation
A3 Mowing/cutting of grassland
J7 Anthropogenic habitat fragmentation
J6 Reduction of prey availability
E1 Urbanisation and development
A4 Abandonment/lack of mowing
B6 Forestry fertilisation
A1 Modification of cultivation
B7 Other forest activities
F2 Illegal killing
H1 Pollution
D4 Aircrafts or flightpaths
E2 Dispersed habitation
D2 Roads, motorways
D1 Paths, tracks, forest roads
B2 Forest management and use
J5 Loss of habitat features
i
ii
iii
iv
150
100
50
0
Height